

Axion luminosity of Active Galactic Nuclei

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Abstract: We compute the flux of axions from Active Galactic Nuclei (AGN). Axions can be produced in the accretion disk by the Compton, Bremsstrahlung & Primakoff processes. We find that the axion luminosity due to these processes is negligible in comparison to the photon luminosity from AGNs. We also compute the luminosity of a hypothetical pseudoscalar, with very small mass, from the AGN atmosphere due to the phenomenon of pseudoscalar-photon mixing in background magnetic field. In this case we find that for some parameter ranges, the pseudoscalar flux can exceed that of photons. We comment on the implications of this result on the observed large scale alignment of optical polarizations from AGNs.

1 Introduction

The cores of Active Galactic Nuclei (AGN), identified as quasars, emit a huge amount of power at visible and ultraviolet frequencies [1]. It obtains its power by the gravitational potential energy of a massive black hole residing at its center [2]. The radiation is emitted by the accretion disk surrounding the black hole. In this paper we compute the luminosity of the invisible axions [3–12] from AGNs. We also consider a hypothetical light pseudoscalar whose couplings and mass are not related to one another. Our motivation for this study is two folds. The pseudoscalar flux from AGNs may be used to impose limits on its mass and couplings. If the pseudoscalar flux is sufficiently large then it might also provide an explanation for the observed large scale alignment of visible polarizations from quasars. Large scale alignment, on distance scales of a Gpc, has been observed in many regions of the sky [13–16]. A statistically significant signal of alignment with the local supercluster has also been observed [13–17]. This effect may be explained in terms of the conversion of photons to pseudoscalars in the local supercluster magnetic field. However this explanation is not consistent with data. The problem arises due to the observed difference in the distribution of polarizations among the Radio Quiet (RQ) and optically selected (O) quasars and the Broad Absorption Line (BAL) quasars. The polarization distribution of the RQ and O quasars peaks at very low values. The magnitude of the mixing required to explain the alignment effect is sufficiently large so as to completely wash out this difference. In Ref. [18] it was suggested that if the pseudoscalar flux from quasars is sufficiently large at visible frequencies, than conversion in the supercluster magnetic field may consistently explain the alignment with supercluster. In this case the alignment is explained in terms of the conversion of pseudoscalars to photons.

We first study the emission of pseudoscalars from the accretion disk via the Compton, Bremsstrahlung and the Primakoff channels. In this calculation we assume the pseudoscalar to be the standard axion. Besides emission from the accretion disk, pseudoscalars may also be produced in the AGN atmospheres due to the conversion of photons to pseudoscalar in the background magnetic field. The probability for this conversion is negligible for the standard axion but can be large if the pseudoscalar mass is very small.

2 Axion Luminosity from the Accretion Disk

The emission rates of the axion via the Compton and Bremsstrahlung & Primakoff channels are given, respectively, by the formulas [19–22],

$$\dot{\epsilon}_a(C) = \frac{40N_A\alpha g_{aee}^2\zeta(6)T^6}{\mu_e\pi^2m_e^4} \quad (1)$$

$$\dot{\epsilon}_a(B) = \frac{64n_en_Zg_{aee}^2Z^2\alpha^2T^{5/2}}{15\rho(2\pi)^{3/2}m_e^{7/2}} \quad (2)$$

$$\dot{\epsilon}_a(P) = \frac{2n_ZZ^2\alpha g_{a\gamma\gamma}^2T^4(6\zeta(4)[\ln(2) - 0.5 - \ln(\frac{\omega_p}{T})] + 7.74)}{\rho\pi}. \quad (3)$$

Here N_A is Avogadro's number, α is the fine structure constant, $\zeta(n)$ is the Riemann zeta function, T is the temperature in the accretion disk, μ_e is the mean molecular weight of electron, m_e is the electron mass, ρ is the density, n_e (n_Z) is the number density of electrons (nucleons), Z is atomic number and ω_p is the plasma frequency. The axion-electron coupling g_{aee} and the axion-photon coupling, $g_{a\gamma\gamma}$, is related to the Peccei-Quinn (PQ) spontaneous symmetry breaking scale, f_{PQ} , by the standard formulas [19]. We assume the DFSZ [9, 10] axion for which f_{PQ} is constrained by observations to be greater than 10^8 GeV [23, 24]. For this limiting value the couplings are found to be, $g_{aee} = 5.0 \times 10^{-12}$ and $g_{a\gamma\gamma} = 8.4 \times 10^{-12}$ GeV $^{-1}$. In these estimates we have set the color anomaly factor to be unity. Although the values of these parameters are model dependent, here we use these values for our estimates.

We next calculate the luminosity of axions from the accretion disk by integrating the emission rates over the disk mass. We assume the thin disk model of the accretion disk. Let ρ denote the density of the disk. It can be replaced by $\frac{\Sigma}{H}$, where Σ is the surface density of the disk and $H = \frac{R^{3/2}C_s}{\sqrt{GM}}$. Here $C_s = 10^6$ cm/s is the speed of sound in the accretion disk medium, G is the Gravitation constant, and M is the mass of the central black hole, roughly equal to 10^{41} gm [25].

2.1 Luminosity due to Compton Scattering

We first compute the luminosity due to Compton scattering. From the formula for the emission rate we get, $\dot{\epsilon}_a(C) = 1.268 \times 10^{-11}T^6$ GeV. The luminosity is given by,

$$L_{comp} = \int \dot{\epsilon}_a(C) dM = 1.72 \times 10^{34} \int \int \int \rho T^6 R dR d\phi dz \text{ erg} - \text{s}^{-1} \quad (4)$$

The 'z' integration is straightforward, $\int dz = H$, where 'z' is the scale height of the disk. We obtain

$$L_{comp} = 1.72 \times 10^{34} \times 2\pi \int_{R_*}^{10^3 R_*} \Sigma T^6 R dR \text{ erg} - \text{s}^{-1} \quad (5)$$

where Σ and T are given by [25],

$$\Sigma = 3.57 \times 10^{33} \left[\frac{1}{R^{3/2}} - \frac{\sqrt{R_*}}{R^2} \right] \text{ erg} - \text{cm}^{-2}, \quad (6)$$

$$T = 1.1 \times 10^{16} \left[\frac{1}{R^3} - \frac{\sqrt{R_*}}{R^{7/2}} \right]^{1/4} \text{ K}, \quad (7)$$

respectively. Using these values, we get, $L_{comp} = 9.7 \times 10^{29} \text{ erg} - \text{s}^{-1}$.

2.2 Bremsstrahlung

The axion emission rate for the bremsstrahlung process is found to be

$$\epsilon_a(B) = 1.461 \times 10^{-16} \rho T^{5/2} \text{ GeV} \quad (8)$$

where both ρ and T are in GeV units. Using Eqs. (6) and (7) we find,

$$\epsilon_a(B) = 1.28 \times 10^{-22} \frac{\Sigma}{R^{3/2}} T^{5/2} \text{ GeV}. \quad (9)$$

The luminosity due to this process is found to be

$$L_{brem} = \int \epsilon_a(B) dM = 5.7 \times 10^{36} \text{ erg} - \text{s}^{-1}. \quad (10)$$

2.3 Primakoff

In this case, the emission rate is given by,

$$\epsilon_a(P) = 3.4567 \times 10^{-25} \left[8.9943 T^4 - 6.4939 T^4 \ln \left(\frac{\omega_p}{T} \right) \right] \text{ GeV} \quad (11)$$

where the plasma frequency,

$$\omega_p = 2.452 \times 10^{13} \frac{1}{R^{3/4}} \left[\frac{1}{R^{3/2}} - \frac{\sqrt{R_*}}{R^2} \right]^{1/2} \text{ GeV}. \quad (12)$$

Therefore, we find that,

$$L_{Prim} = 2.84 \times 10^{32} + 7.1 \times 10^{31} \text{ erg} - \text{s}^{-1} \quad (13)$$

We find that the axion emission rate is relatively small due to all the three processes. It is negligible compared to the AGN's photon luminosity. The dominant contribution is obtained by the bremsstrahlung process.

The calculation in this section depends only on the coupling of the axion to fermions and photons and does not depend on its mass. Hence the result is also valid for a hypothetical pseudoscalar with similar couplings but whose mass may not be related to the PQ symmetry breaking scale as long as the mass is much smaller than the accretion disk temperature.

We note that in our study we have made several approximations. For example, we have used the thin disk approximation in our study, which may not be true in reality. Actually, our usage of the thin disk model is forced since no other viable stable model is available. Furthermore we have not investigated the pseudoscalar emission rate from the interiors of the AGN's or from other parts such as jets, etc.

3 Conversion In AGN Surroundings

In section 2 we have found that the total axion luminosity of the accretion disk is negligible compared to the total photon luminosity. Here, we determine the contribution to the pseudoscalar luminosity due to photon to pseudoscalar conversion in the AGN surroundings due to the background magnetic field. By AGN surroundings, we mean the atmosphere outside the accretion disk. This includes the dust tori, broad line region and the narrow line region. In order to perform this calculation, we require parameters such as the plasma density, magnetic field etc. in this region, which are unknown. Hence, we instead use the parameters corresponding to the radio lobes. We shall take the representative values for Cygnus A to estimate the pseudoscalar luminosity. The actual parameters may vary and hence our estimates may only be qualitatively reliable.

We point out that we are not considering the standard Peccei-Quinn axion in this section. Rather, we look at a generic pseudoscalar whose mass and couplings to visible matter are unrelated to each other. The present bound on the axion mass is relatively large. For such a large mass, the conversion probability of axion into photon is found to be negligible. Instead, here we assume that $m_\phi \lesssim \omega_p$, where ω_p is the typical plasma frequency in the radio lobes. In this case the conversion probability may be significant.

The pseudoscalar-photon mixing phenomenon in background magnetic field has been analyzed in great detail in the literature [26–41]. This phenomenon has also been used to impose stringent limits on the pseudoscalar-photon coupling [42–57]. A beam of photons, passing through background magnetic field, would convert partially into pseudoscalars due to this mixing phenomenon. The mixing probability increases with frequency. At very high frequencies the mixing probability is very large and hence the flux of pseudoscalars produced may be comparable to the incident photon flux. As the pseudoscalar flux becomes sizeable, we expect significant pseudoscalar to photon conversion. Eventually we expect a beam containing roughly equal number of photons and pseudoscalars. This is true as long as the extinction of photons is negligible in the medium. However if extinction is significant, we may obtain larger pseudoscalar luminosity, even if the incident beam consists entirely of photons. The extinction coefficient for AGN atmospheres is not known. Here we shall assume that the extinction is of same order of magnitude in comparison to what is observed in the host galaxies in the case of high redshift supernovas [58]. Here the visual extinction coefficient is extracted from the observed light curve for these supernovas. In the present case, in order to compute the pseudoscalar flux at visible frequencies, we need to extrapolate the extinction coefficient to ultraviolet frequencies. This is because a source at high redshift must emit UV light so that the radiation received by us is in the visible band. The extinction depends approximately linearly on the frequency of the photons. Hence, we obtain the extinction at UV frequencies by suitably rescaling the extinction observed at the visible region in supernovae data [58] at large redshifts.

We next briefly review the formalism for pseudoscalar-photon mixing in a uniform background, to the case where the medium causes extinction of photons. An earlier discussion of this phenomenon may be found in [59]. Using the notations used in [32], we write the differential equation of mixing with extinction, ignoring the longitudinal component of the photons and the mixing of transverse components thereof [32], as follows,

$$(\omega^2 + \partial_z^2) \begin{bmatrix} A_{||}(z) \\ \phi(z) \end{bmatrix} = M \begin{bmatrix} A_{||}(z) \\ \phi(z) \end{bmatrix}. \quad (14)$$

This equation describes the mixing of the parallel component of the electromagnetic field with the pseudoscalar ϕ . The perpendicular component A_\perp does not mix with ϕ . The “mass matrix” or the “mixing matrix” in Eq. (14) can be written as,

$$M = \begin{bmatrix} \omega_p^2 + i\Gamma(\omega) & -g_\phi \mathcal{B}_T \omega \\ -g_\phi \mathcal{B}_T \omega & m_\phi^2 \end{bmatrix} \quad (15)$$

where \mathcal{B}_T is the transverse component of the background magnetic field and $\Gamma(\omega)$ describes the attenuation of photons due to their extinction in the medium. We note that the extinction of light is modelled with a parameter called optical depth, τ_ν , such that the intensity $I_\nu(z) = I_\nu(0)e^{-\tau_\nu}$, where z is the thickness of the medium. In general the optical depth increases linearly with frequency. Hence we may assume $\tau_\nu = K\omega$, where K is a constant. In our formulation, the exponential decay parameter is $\frac{\Gamma z}{2\omega}$, at leading order. Equating this to τ_ν we find $\Gamma = \frac{2\omega^2 K}{z}$. As discussed above, we shall fix the value of K by assuming that at visual frequencies the extinction is similar to that observed for high redshift supernovas [58]. This leads to $\Gamma \approx 2.8 \times 10^{-28} \omega^2 (\tau/0.5)$, where ω is expressed in Hz and the visual extinction $A_V = (2.5 \log_{10} e)\tau$.

We can solve the equations, Eq. 14, by diagonalizing the matrix M . The eigenvalues of this matrix, λ_+ and λ_- may be expressed as,

$$\lambda_\pm = \frac{1}{2} \left[\Omega_p^2 + m_\phi^2 \pm \sqrt{(\Omega_p^2 + m_\phi^2)^2 - 4(\Omega_p^2 m_\phi^2 - g_\phi^2 \mathcal{B}_T^2 \omega^2)} \right] \quad (16)$$

where $\Omega_p^2 = \omega_p^2 + i\Gamma$. We assume the boundary condition, $\phi(0) = 0$, and find the final result

$$\begin{aligned} A_{||}(z) &= \frac{1}{ad - bc} \left[ad e^{(iz\sqrt{\omega^2 - \lambda_+})} - bc e^{(iz\sqrt{\omega^2 - \lambda_-})} \right] A_{||}(0) \\ \phi(z) &= \frac{bd}{ad - bc} \left[e^{(iz\sqrt{\omega^2 - \lambda_+})} - e^{(iz\sqrt{\omega^2 - \lambda_-})} \right] A_{||}(0), \end{aligned} \quad (17)$$

where $a = (\lambda_+ - m_\phi^2)/\sqrt{N_+}$, $b = -g_\phi B_T \omega / \sqrt{N_+}$, $c = g_\phi B_T \omega / \sqrt{N_-}$, $d = (\Omega_p^2 - \lambda_-)/\sqrt{N_-}$. Here N_+ and N_- are normalization factors which cancel out in the final expressions. The perpendicular component of the electromagnetic wave is given by,

$$A_{\perp}(z) = A_{\perp}(0) e^{iz\sqrt{\omega^2 - \Omega_p^2}} \quad (18)$$

Using Eq. 17 and Eq. 18 we can compute the photon and pseudoscalar flux emerging out of the AGN atmosphere. In making this calculation we assume parameters corresponding to the Cygnus A radio lobe. Hence we set the plasma density $n_e = 10^{-4} \text{ cm}^{-3}$ and magnetic field $B_T = 4 \times 10^{-4} \text{ G}$. We assume the pseudoscalar photon coupling, $g_{\phi\gamma\gamma} = 10^{-10} \text{ GeV}^{-1}$ and the pseudoscalar mass is set to zero.

In Fig. 1 we show the pseudoscalar and photon intensity as a function of the frequency setting the distance equal to 10 Kpc. Here we have set the extinction parameter $\tau = 0.1$ and ω represents the frequency at source. In this plot we have normalized the intensity such that the photon intensity is unity before entering the AGN atmosphere. In Fig. 2 we show the ratio of the pseudoscalar to photon intensity as a function of frequency. We find that the pseudoscalar intensity is significantly larger in comparison to the photon intensity at higher frequencies. For the parameters chosen, the pseudoscalar intensity is a factor of two or three larger than the photon intensity for $\omega = 5 \times 10^{16}$ to 10^{17} Hz . For larger frequencies the pseudoscalar flux may be an order of magnitude higher in comparison to the photon flux. However here the overall flux may be very small.

In our calculations we have set the pseudoscalar mass to zero. If the pseudoscalar mass is comparable to the plasma density of the medium then there is also the possibility of resonant mixing of pseudoscalars with photons [32]. In this case the photon to pseudoscalar conversion is considerably enhanced and hence the pseudoscalar flux from AGNs may be significantly higher.

4 Alignment of Quasar Polarizations

We next briefly address the issue of alignment of optical polarization from quasars in the direction of the Virgo supercluster. This region is labelled as A1 in [13, 14]. Here we limit ourselves to a qualitative explanation. A detailed quantitative analysis is postponed for future research.

The alignment effect may in principle be explained by the conversion of photons into pseudoscalars in the Virgo supercluster magnetic field [13, 14, 18]. However, as mentioned in the introduction, this does not consistently explain the data due to the observed distribution of polarization of the RQ and O quasars [13, 14]. The polarization distribution of these quasars is found to peak at very low values. In contrast the distribution of BAL quasars is observed to be much broader. The difference between these two classes of quasars is seen in all directions including the A1 region. The magnitude of the systematic effect required to explain alignment is sufficiently large that it would completely distort the distribution of RQ and O quasars. We may alternatively consider the possibility that quasars emit a significant amount of pseudoscalar flux, as found in the previous section. The pseudoscalar flux is assumed to be larger than the photon flux. In this case the alignment may be explained in terms of the conversion of pseudoscalars into photons in the Virgo supercluster. This will lead to a linear polarization aligned along the transverse component of the background magnetic field. Furthermore we assume that the ratio of the pseudoscalar to photon flux is much larger for the BAL quasars in comparison to the RQ and O quasars. Hence the systematic polarization effect due to pseudoscalar-photon mixing would be smaller for RQ and O quasars in comparison to BAL quasars. Since the RQ and O quasars in general have smaller degree of polarization, this may be sufficient to explain their alignment. In contrast

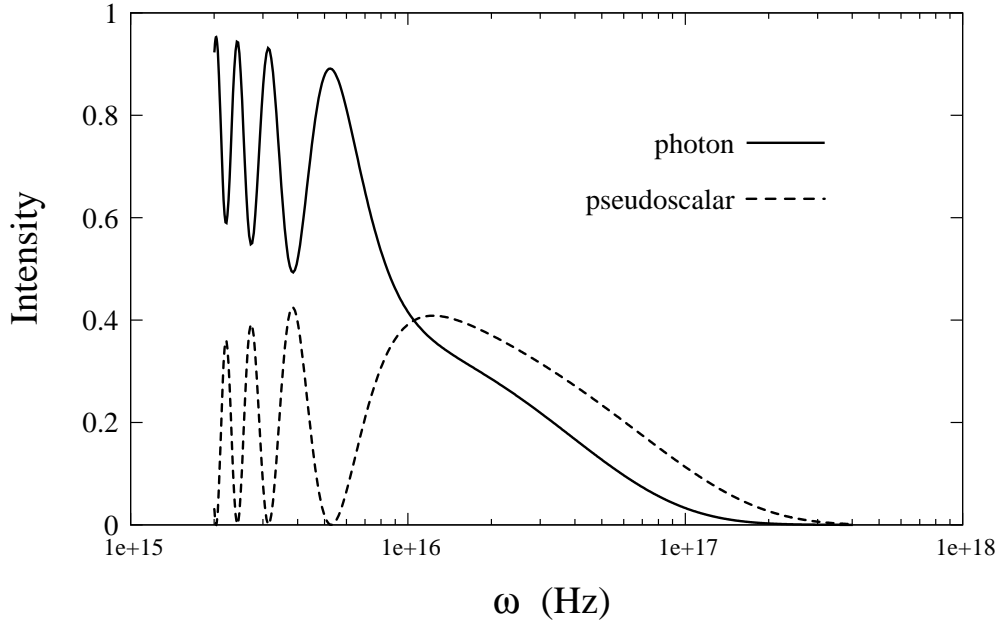


Figure 1: The pseudoscalar and photon intensity as a function of the frequency.

the BAL quasars would get a larger contribution due to pseudoscalar-photon mixing, which is required due to their larger intrinsic polarization. Hence we find that the observed alignment may be consistently explained if the quasars emit pseudoscalars.

5 Conclusions

In this paper, we have found that the luminosity of pseudoscalars from the AGN accretion disk due to Compton, Bremsstrahlung and Primakoff channels is very small in comparison to the photon luminosity. However, the photons in visible and ultraviolet frequencies may convert to pseudoscalars outside the accretion disk due to pseudoscalar-photon mixing in the background magnetic field. Taking extinction of photons into account and using the current limit on the pseudoscalar-photon coupling, we find that the pseudoscalar flux produced by this process is relatively large. For ultraviolet frequencies, which would be observed in the visible range on earth, this flux may dominate the photon flux. A large pseudoscalar flux may provide a consistent explanation for the large scale coherent orientation of the visible polarizations from quasars.

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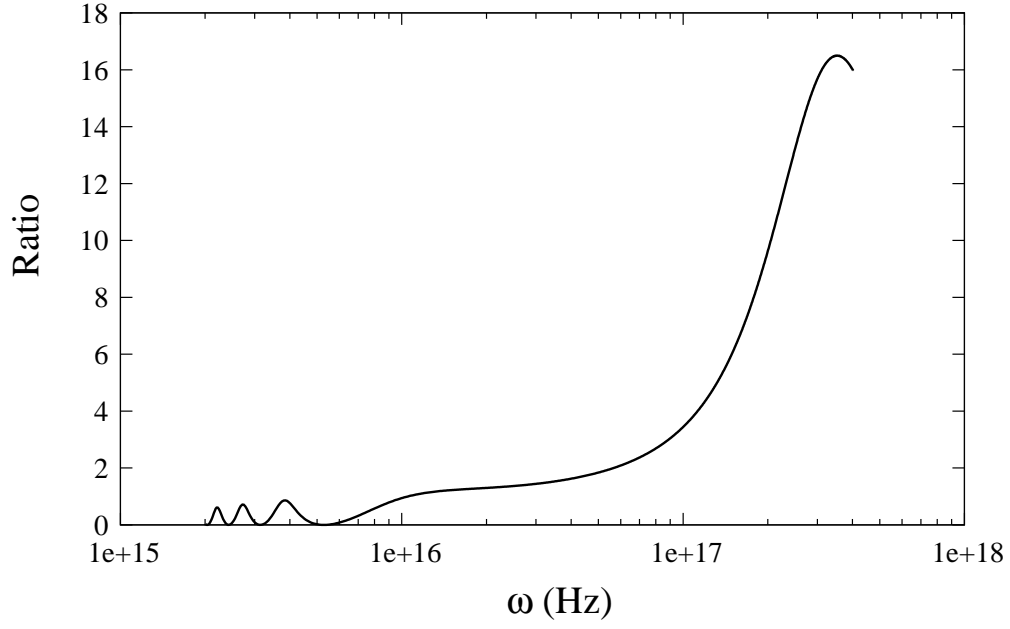


Figure 2: The ratio of pseudoscalar to photon intensity as a function of the frequency.

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